

# **Contrails Over the U. S. and Their Potential Impact on the Radiation Budget**

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A methodology for assessing the contrail impact on the radiation budget is developed to use data characterizing the frequency, areal coverage, optical depth, particle size, and altitude of contrails with observations of cloud and surface properties. The method is tested using various scenarios over the United States to estimate contrail-induced albedo changes based on current aircraft fuel usage statistics. The technique can be used for estimating infrared effects and the impact of future fuel-use rates.

## **1. INTRODUCTION**

Increases in cloud cover due to contrails can alter the local radiative balance by reflecting more solar radiation and absorbing and emitting longwave infrared radiation [1]. Under certain conditions, such changes can affect regional weather and climate. The overall effect of contrails on climate depends on a number of factors including frequency and timing of occurrence, areal coverage, lifetime, altitude, location, and microphysical properties. Because the upper troposphere is a relatively clean (aerosol-free) environment, the addition of high concentrations of cloud condensation nuclei have the potential for making a larger impact than they would in the lower troposphere. With commercial air traffic expected to increase by more than 200 percent by 2015 [2], the effects of aircraft exhaust on the atmosphere have become a subject of considerable interest leading to the NASA Atmospheric Effects of Aircraft Program (AEAP), sponsor of the Subsonic Assessment (SASS) Project [3]. One of the SASS goals is the evaluation of the contrail effect on climate. This paper develops a new approach for assessing the radiative impact of contrails, the first step to understanding the overall climatic effect.

Only a few satellite analyses have been performed to determine the change in cloudiness due to contrails. For example, Bakan et al. [4] used visual analysis of thousands of quicklook from the NOAA Advanced Very High Resolution Radiometer (AVHRR) infrared images taken over the northeast Atlantic and Europe to estimate contrail cloudiness for 1979-1981 and 1989-1992. They found a distinct seasonal cycle with a southward displacement of the contrail maximum during winter. Maximum contrail coverage in their analysis occurred during summer centered along the North Atlantic air routes. The coverage over that area increased during the 10-year interim. Similar analyses over the air corridors of the U.S. have not yet been performed. In this paper, a new surface-based contrail occurrence data base is used to estimate potential changes in albedo over the United States due to contrail-cloud cover. A modeling approach is used to relate aircraft fuel usage to contrail-enhanced cloud cover and ultimately to albedo changes.

## 2. METHODOLOGY

For a given area and local time  $t$ , the albedo  $\alpha$  at the top of the atmosphere can be described simply as a linear combination of the cloudy and clear albedos or

$$\alpha_{nat}(t, \phi, \lambda) = \alpha_{clr}(t, \phi, \lambda)(1 - C) + \alpha_{cld}(t, \phi, \lambda) C. \quad (1)$$

where the fractional cloud cover is  $C$ , the subscripts  $nat$ ,  $clr$ , and  $cld$  refer to natural or contrail-free, clear, and cloudy, respectively, and  $\phi$  and  $\lambda$  are latitude and longitude, respectively. The albedo for the same region in the presence of contrails can be estimated as

$$\alpha_{CON}(t, \phi, \lambda) = \alpha_{CLRC}(t, \phi, \lambda)(1 - C) + \alpha_{CLDC}(t, \phi, \lambda) C. \quad (2)$$

The albedo for the portion of the scene that contains contrails over an otherwise clear background is

$$\alpha_{CLRC}(t, \phi, \lambda) = \alpha_{clr}(t, \phi, \lambda)(1 - c_{clr}) + \alpha_{con}(t, \phi, \lambda) c_{clr}, \quad (3)$$

where  $c_{clr} = c(2 - f_{cld} / C)$ ,  $c$  is the average contrail fractional coverage for the area, and  $f_{cld}$  is the fraction of the time that an area is overcast by clouds. Similarly, the cloudy albedo when contrails overlay the clouds is

$$\alpha_{CLDC}(t, \phi, \lambda) = \alpha_{cld}(t, \phi, \lambda)(1 - c_{cld}) + \alpha_{cldc}(t, \phi, \lambda) c_{cld}, \quad (4)$$

where  $c_{cld} = c f_{cld} / C$ . The total albedo is

$$\alpha_{tot}(t, \phi, \lambda) = \alpha_{nat}(t, \phi, \lambda)(1 - f) + \alpha_{CON}(t, \phi, \lambda) f, \quad (5)$$

where the frequency of contrail occurrence is

$$f = f(t, \phi, \lambda). \quad (6)$$

To determine the overall effect, the albedo must be integrated over all local times to determine the albedo for the entire day. The mean daily albedo in all conditions is

$$\alpha_{TOT}(\phi, \lambda) = \frac{\sum \alpha_{tot}(t_i) \mu_o(t_i) \Delta t_i}{\sum \mu_o(t_i) \Delta t_i} \quad (7)$$

where  $\mu_o$  is the average cosine of the solar zenith angle for the time interval of length  $\Delta t_i$  centered at time  $t_i$ , and  $i$  is the subscript denoting a particular mean local time. The mean daily albedo in the absence of contrails is

$$\alpha_{NAT}(\phi, \lambda) = \frac{\sum \alpha_{nat}(t_i) \mu_o(t_i) \Delta t_i}{\sum \mu_o(t_i) \Delta t_i} \quad (8)$$

The albedo change due to the contrails is

$$\Delta\alpha(\phi, \lambda) = \alpha_{TOT} - \alpha_{NAT}. \quad (9)$$

A reasonable estimate of the monthly mean albedo change over a given month can be derived using (9) with the monthly mean contrail frequencies and cloud cover, effective solar zenith angles, and mean cloudy and clear-sky albedos at each local hour.

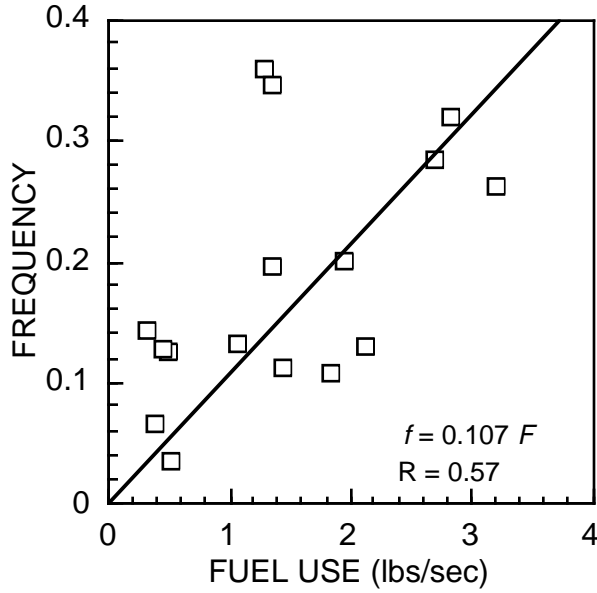


Fig. 1. Comparison of 3° regional fuel use in upper troposphere to mean contrail frequencies for U.S. sites during April. Line is regression fit.

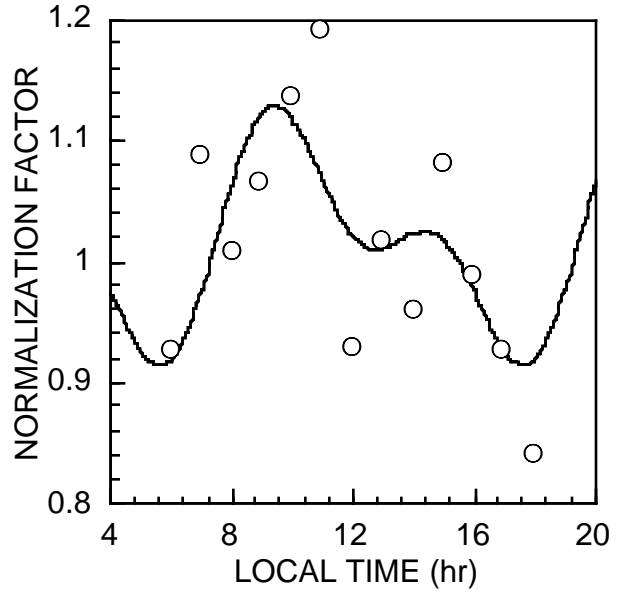


Fig. 2. Mean hourly contrail frequencies for 19 U.S. sites during April relative to the average of 0.19. Curve is a second-order harmonic fit to the data.

### 3. DATA AND ANALYSIS

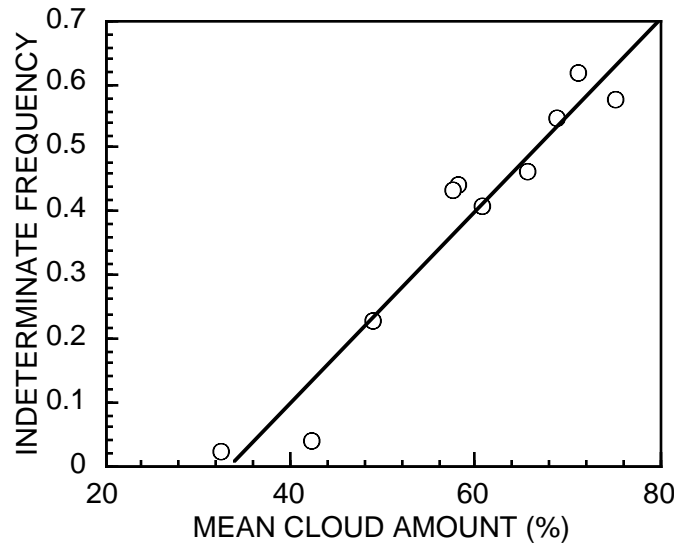
The area between 28°N to 49°N and 61°W to 124°W was gridded into 3° x 3° boxes and used to represent the continental U.S. Baughcum (1996) recently produced Estimates of the 1992 scheduled [5] and other [6] monthly mean aircraft fuel usage as a function of altitude were combined on a 1° latitude-longitude grid over the world. Because most long-distance aircraft fly above 8 km, the fuel usage for each month was averaged for each 3° box between 8 and 14 km to yield  $F(\phi, \lambda)$  where  $\phi$  and  $\lambda$  are referenced to the center of the box. Monthly mean persistent contrail frequencies for 19 locations over the U.S. from 1993 and 1994 [7] were correlated with the 8-14 km average fuel use rate for the nine 1° boxes nearest to the surface site. It is assumed that fuel use rates were essentially unchanged between 1992 and 1994. The frequency data are computed relative to the number of hours when it was possible to see contrails. Contrails were indeterminate when overcast conditions prevailed. It is assumed here that contrail frequency is the same for both unobscured and indeterminate conditions.

Figure 1 shows the scatterplot and regression line for April where

$$f = bF, \quad (10)$$

For this case, the coefficient  $b$  is 0.107; the coefficient of correlation is  $R = 0.57$ ; the monthly mean contrail frequency is 0.183; and  $F$  is given in pounds per second. This relationship is used to estimate  $f$  at locations over the U.S. during April. Similar correlations were performed for each month and a harmonic fit was applied to the results to obtain a smooth variation of  $b$  with time. The peak and minimum values of  $b$  occur during February and July, respectively. The variation of  $b$  empirically accounts for the meteorological dependence of contrail occurrence. The diurnal dependence of contrail frequency was estimated using monthly hourly means for the 19 sites and normalizing the data to the 19-site monthly mean. The expected frequency of occurrence at a given hour is  $f(t) = \delta(t) f$ , where  $\delta$  is the normalization factor for hour  $t$ .

Cloud amounts consist of monthly means derived from the 1985 International Satellite Cloud Climatology Project (ISCCP) C2 product [8]. These means were interpolated to match the 3° grid boxes used here. The surface-based observations of indeterminate contrails were correlated to the



*Fig. 3 - Mean cloud amount and indeterminate contrail frequency for 19 U.S. sites during April with regression fit.*

monthly mean surface-observed cloud fraction to determine how often contrails would occur over other clouds. A simple linear relationship,

$$f_{cld} = b_0 + b_1 C, \quad (11)$$

was used to represent the relative frequency of contrails over clouds. The scatterplot and fit for April is shown in Fig. 2, where  $b_0 = -0.504$  and  $b_1 = 0.0152$ . The coefficients were fitted to a second order harmonic to produce a smoothly varying set of conversion lines for each month. Using the ISCCP data to find  $C$  for a given region and month, it is possible to determine  $f_{cld}$  from (11),  $f$  from (10), and  $f_{clr}$  from (6). The mean cloud optical depths,  $\tau$ , were also computed from the ISCCP C2 data.

Albedos at the top of the atmosphere were calculated using the methodology of Charlock et al. [9] that is based on the radiative transfer model of Fu and Liou [10]. Standard midlatitude winter and summer atmospheres were used for the appropriate months and an average of the two was used for spring and fall months. Surface albedo was specified using a land type map and the method of Briegleb et al. [11] was used to relate albedo to surface type. The monthly mean cloud optical depth was inserted at 5 km and the contrail optical depth  $\tau$  was placed at 10.5 km. Contrail coverage was varied from 0 to 100%. The contrail optical depths were 0.05, 0.1, 0.2, and 0.3. The cloud particle effective radius was specified at 10  $\mu\text{m}$  and the contrail crystal effective diameter was set at 24  $\mu\text{m}$ . The clear and cloudy albedos were computed at each local time for both contrail and contrail-free conditions in a given region.

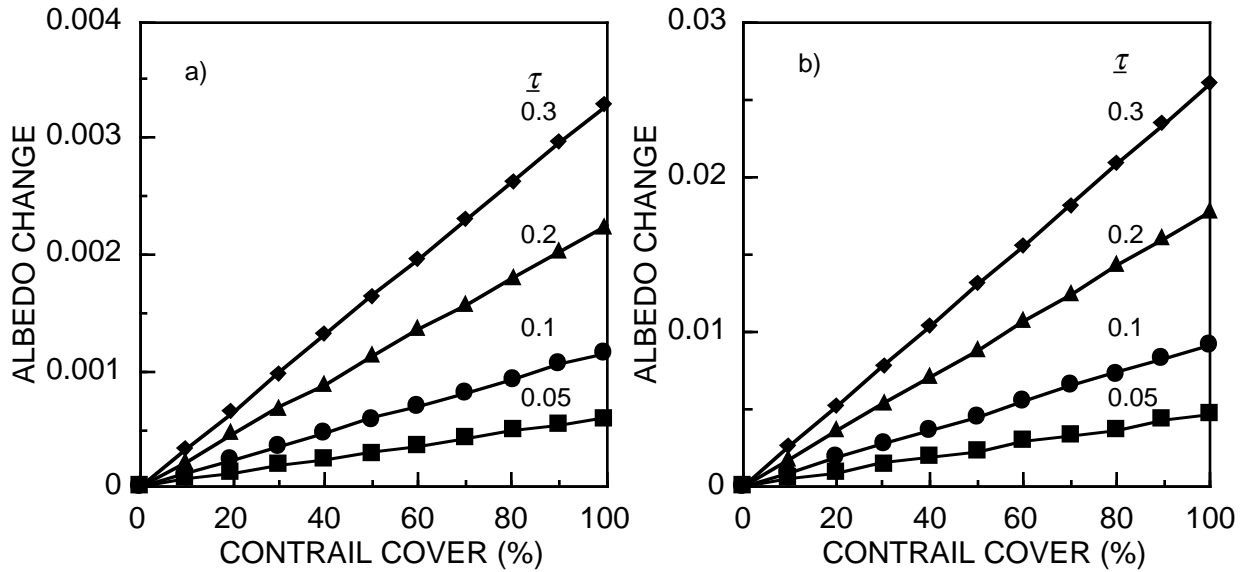


Fig. 4. Estimated albedo change over the U.S. during April due to contrails of various optical depths for (a) observed frequency and (b) 100% frequency.

#### 4. RESULTS

Figure 4 shows the mean change in albedo for April using the April 1990 ISCCP dataset. The mean frequency of contrail occurrence over the U.S. for April is approximately 10% based on the model used here. Thus, the changes in albedo for the observed frequencies (Fig. 4a) are almost an order of magnitude smaller than the 100% frequency case. The mean ISCCP cloud cover for the domain is  $\sim 0.65$  so the value of  $f_{cld}$  is  $\sim 0.43$ . Assuming an average albedo of 0.38 for the domain, the change of 0.001 for  $c = 30\%$  and  $\tau = 0.3$  is a minor change of only 0.3%. A 1% increase in the albedo would require the contrails to completely fill a given  $3^\circ$  box with an optical depth of 0.3, an unlikely scenario. If the contrails occurred at all times (Fig. 4b), the albedo change would be quite noticeable. As seen in Fig. 5b, 30% coverage by the contrails with  $\tau = 0.3$  would cause a shortwave cooling of almost  $4 \text{ Wm}^{-2}$  if the contrails always occurred, also an improbable event. If the current frequency is used, the corresponding decrease in shortwave flux to the system is only  $\sim 0.4 \text{ Wm}^{-2}$ . The change in albedo or shortwave flux also depends on cloud amount because the impact of contrails on albedo is relatively minor when they are over another cloud.

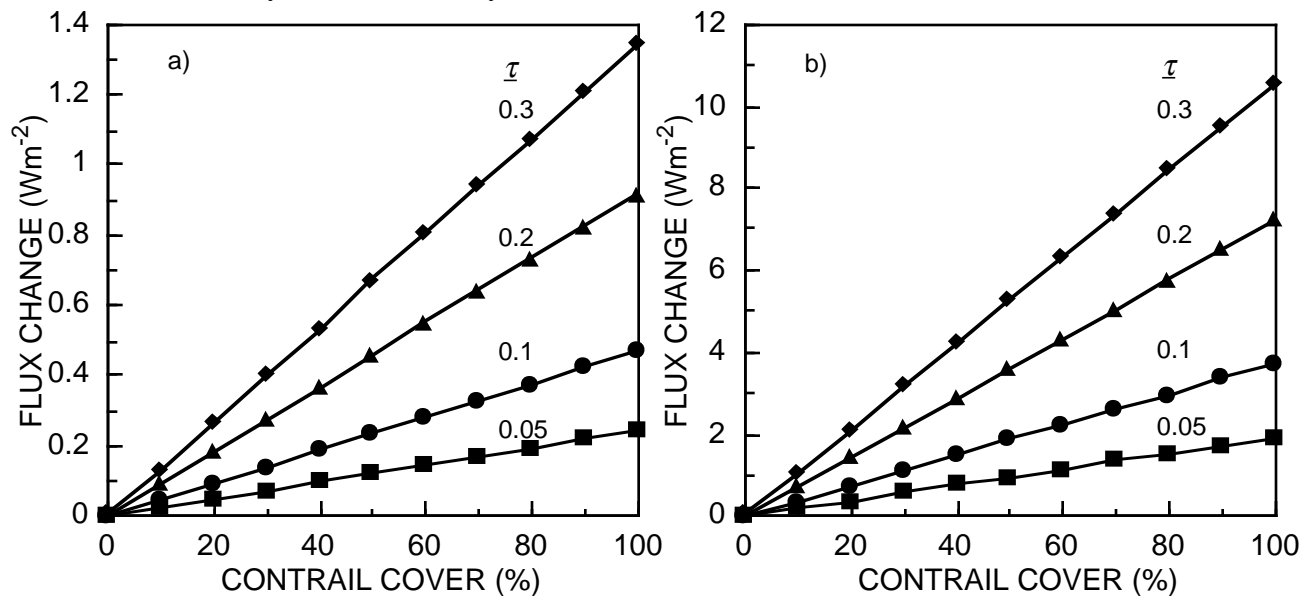


Fig. 5. Same as Fig. 4 except for change in mean reflected shortwave flux.

The mean differences in albedo shown in Fig. 4 do not accurately portray the regional variability in the albedo change. Maximum increase in albedo, 0.003 ( $\tau = 0.2$ ,  $c = 30\%$ ) would be expected over the midwestern U.S. from Chicago to New York with a secondary maximum from Miami to Charleston, South Carolina. The contrail albedo change is even seen 1000 km off the North Carolina coast. A third maximum would be expected over southern Nevada where it is relatively clear and air traffic is heavy. Minimum albedo changes are found over the northern tier of the U.S. and northern Mexico. Although fuel use patterns are the predominant influence on the albedo changes, the correspondence is not entirely straightforward because of the cloud patterns.

## 5. CONCLUDING REMARKS

A methodology for studying the impact of contrails on the radiation budget has been developed using realistic fuel usage-contrail occurrence data, cloud observations, and surface albedos. This method can also be adapted to examine the longwave warming effects of contrails and used to study the effects of projected increases in fuel usage and changes in flight corridors. In this study, only 1 month of data over the U.S. was examined to study the impact of contrails albedo. Other months and areas can be examined given the proper relationship between fuel use, contrails, and weather conditions. Much additional information is also needed to determine the best values for contrail optical depth, coverage, and lifetimes.

## 6. REFERENCES

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